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SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
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3. DISCUSSION. This research is funded by AFOSR and the NSF.

4. VIEWS OF OTHERS. N/A

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Tabs
1.

Methodology of evaluating the science benefit of various satellite/sensor constellation orbital parameters to an assimilative data forecast model.

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Key Points

Methodology for evaluating benefit of increasing assimilative data sources

Abstract

A methodology for evaluating the science benefit of adding space weather sensor data from a modest number of small satellites to the Utah State University Global Assimilation of Ionospheric Measurements – Full Physics (GAIM-FP) model is presented. . Three orbital scenarios are presented, two focusing on improved coverage of narrowly specified regions of interest, and one on global coverage of the ionosphere as a whole. An Observing System Simulation Experiment (OSSE) is used to obtain qualitative and quantitative results of the impact of the various orbital scenarios on the ionospheric specifications. A simulated "truth" run of the ionosphere is obtained from a first principles model of the Ionosphere/Plasmasphere model (IPM) and used to generate global simulated Global Positioning Satellite Total Electron Content (GPS-TEC) data as well as in-situ plasma density observations. Initially, only GPS data were assimilated by GAIM-FP and the results of this limited run were compared to the truth run. Next, the simulated in-situ plasma densities corresponding to our three orbital scenarios were assimilated together with the GPS data and the results were compared to both the truth run and the limited GPS-TEC only GAIM-FP run. These model simulations have shown that adding a constellation of small satellites/sensors in addition to global TEC inputs does indeed converge the GAIM-FP model closer to "truth" in the situations described.

Index Terms and Keywords

Ionosphere: Instruments and Techniques

Ionosphere: Modeling and Forecasting

Radio Science: Instruments and Techniques

1. Introduction

In recent years, there have been constructed or proposed space sensor networks [*Anderson* et al, 2002; *Barnhart* et al, 2007a, 2007b; *Barnhart*, 2008; *Barnhart* et al, 2009; *Vladimirova* et al, 2011; *Dyrud* et al, 2013] designed to cover selected orbits in LEO with either:

i) low-cost redundant "disposable" spacecraft-as-sensor platforms of CubeSat 3U size or smaller, or

ii) low-cost low-SWAP (Size, Weight and Power) sensors designed to be placed on as many conventional (ESPA-class or larger) satellites as possible.

The science objective of these missions is to provide a dense set of sensor data parameters to "fill in the gaps" of the relatively sparse coverage afforded by conventional multi-million-dollar missions [*de la Beaujardiere*, 2004] which produce single-point in-situ or remote measurements.

Despite the lower cost of small satellites andlow-SWAP instrumentation, limitations include funding, choice of orbital parameters in launch opportunities, space debris mitigation, and data volume/bandwidth consideration. A key question asked by funders and approvers is still "how many satellites/sensors are enough?" What has become apparent is that there is no generally agreed metric for determining the scientific justification side of this argument, and we propose one methodology to obtain quantitative metrics which may assist in answering that question.

2. Scientific Problem and Background

The science problem that we identify for this study is space weather forecasting, particularly forecasting of plasma irregularities ("plasma bubbles") that cause radio and GPS scintillation. Such scintillation can cause loss of GPS lock (less than 50% availability for LPV-200 during severe scintillation [*Seo*, 2010]), loss of communications, and image defocussing in synthetic aperture radar. Forecasting (and nowcasting) ionospheric conditions conducive to plasma bubble formation would seem to require global assimilative models of the ionosphere to provide baseline conditions in the regions of interest.

Our ability to specify and forecast ionospheric dynamics and ionospheric weather at low and mid latitudes is strongly limited by our current understanding of the coupling processes in the ionosphere-thermosphere system and the coupling between the high and low latitude regions. Furthermore, only a limited number of observations are available for a specification of ionospheric dynamics and ionospheric weather at these latitudes. As shown by meteorologists and oceanographers, the best specification and weather models are physics-based data assimilation models that combine the observational data with our understanding of the physics of the environment [*Daley*, 1991]. Through simulation experiments these models can also be used to study the sensitivity of the specification accuracy on different arrangements of observation platforms and observation geometries and can provide important information for the planning of future missions. For example, these studies can provide information about the number of spacecraft needed to improve the specification or evaluate the impact of different observation geometries on the accuracy of the specification.

3. Instrument and Satellite Concept

Previous efforts in flying low-cost space weather instruments have focused on low-impact secondary payloads riding on larger (e.g ESPA-class) satellites. These have advantages, in that the larger satellites tend to be more reliable (through extensive heritage and testing) and have larger link budgets and power margins. However, there are higher integration costs (particularly when co-riding with high-value primary payloads), longer project timescales, and more expensive busses ($10M+). They also provide only a few in-situ measurements for each satellite, and have relatively long delays before resampling the same dataspace.

There have, however, been recent advances in thinking regarding multiple low-cost redundant satellites carrying low-cost sensors.. Such a large constellation has many applications; treaty sentinels, disaster monitoring, magnetospheric observations, solar wind measurements, pollution monitoring and communications research to name but a few. In many of the above cases we currently undersample the data field. We concentrate our approach for this paper on the thermosphere/ionosphere system, ingesting plasma density and temperature data from in-situ measurements into an assimilative model, although the general methodology is applicable to any of the above applications.

With this approach there are a number of suitable instruments with low SWAP that obtain in-situ ionospheric parameters (we restrict ourselves to in-situ measurements for this study, although a similar methodology may be used with remote measurements). The MESA (Miniaturized ElectroStatic Analyzer) instrument [*Enloe* et al, 2002] is a bandpass or high-pass energy filter (in either of two configurations). The instrument thus measures ion or electron spectra (convolved with the instrument response function) from which plasma density and temperature can be derived. MESAs have flown on MISSE-6, MISSE-7 [*Jenkins* et al, 2009], ANDE-2,

FalconSAT-5, STP-H4 and STPSat-3, and are rostered to fly on OTB and other missions. Another instrument of interest is WINCS (Winds Ions Neutrals Composition Suite) and its sister instrument SWATS (Small Wind And Temperature Spectrometer), developed by the Naval Research Laboratory. WINCS and SWATS are sensor suites measuring ion and neutral winds, temperature and composition (http://www.nrl.navy.mil/ssd/branches/7630/SWATS). More generic/traditional Langmuir probes and Retarding Potential Analyzers are also instruments that may with care be integrated into a low SWAP package (although the standoff length of a Langmuir probe may prove to be challenging).

4. GAIM-FP Comparison Methodology

At Utah State University, we have developed two physics-based Kalman-filter data assimilation models for the Earth ionosphere. The two models are the Gauss-Markov Kalman Filter Model (GAIM-GM) and the Full Physics-Based Kalman Filter Model (GAIM-FP) [*Scherliess et al.*, 2006, 2009)]. Both models are part of the Global Assimilation of Ionospheric Measurements (GAIM) project (*Schunk et al.* 2004) . Some of the data that we have previously assimilated in our data assimilation models include in-situ electron density measurements from DMSP satellites, bottomside electron density profiles from ionosondes, GPS-TEC data from a network of up to 1000 ground stations, ultraviolet (UV) radiances from the SSUSI (Special Sensor Ultraviolet Spectrographic Imager), SSULI (Special Sensor Ultraviolet Limb Imager), and LORAAS (Low Resolution Airglow and Aurora Spectrograph) instruments, and radio occultation data from CHAMP (Challenging Minisatellite Payload) andSAC-C (Satellite de Aplicaciones Cientificas-C) (Hajj et al, 2004)IOX (Ionospheric Occultation Experiment) (*Straus*

et al, 2003), and the COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) (*Rocken et al*, 2000) satellite.

The Full Physics-Based Kalman filter model is based on an ensemble Kalman filter approach (Evensen, 2003) and rigorously evolves the ionosphere and plasmasphere electron density field and its associated errors using a physics-based Ionosphere-Plasmasphere model (IPM) [*Schunk* et *al.*, 2004, 2005; *Scherliess et al.*, 2004]. The IPM is based on a numerical solution of the ion and electron continuity and momentum equations and covers the low and mid-latitudes from 90 to 30,000 km altitude. In its current version, the model excludes geomagnetic latitudes poleward of $\approx \pm 60°$ geomagnetic latitude due to the vastly different physical processes that govern the high-latitude regions, e.g. convection electric fields, particle precipitation, etc. The Full Physics-Based data assimilation model provides specifications on a spatial grid that can be global, regional, or local and its output includes the 3-dimensional electron and ion (NO^+, O_2^+, N_2^+, O^+, H^+, He^+) density distributions from 90 km to geosynchronous altitude (30,000 km). In addition, the model provides the global distribution of the ionospheric drivers (electric field, neutral wind, and composition) that are consistent with the ionospheric observations. It is important to note that the estimation of the ionospheric drivers is an integral part of our ensemble Kalman filter and is achieved by using the internal physics-based model sensitivities to the various driving forces. In this procedure, the ionospheric data are used to adjust the plasma densities and its drivers so that a consistency between the observations (within their errors) and the physical model is achieved. As a result the assimilation procedure produces the optimal model-data combination of the ionosphere-plasmasphere system with its self-consistent drivers (electric fields and neutral winds and composition) [*Scherliess et al.*, 2009, 2011].

5.1 Kalman Filter Simulations

The Full Physics-Based data assimilation model was designed to specify ionospheric weather, but the model can also be used to study the sensitivity of the specification accuracy on different arrangements of observation platforms and observation geometries and can provide important information for the planning of future missions [*Atlas,* 1997; *Atlas et al.,* 1985]. For the current study this latter mode has been used and simulation experiments have been performed. In this mode the model uses a Data Simulation System Experiment (OSSE) using two different synthetic (model-generated) data types: slant TEC from ground-based GPS stations and in-situ plasma density measurements obtained from electrostatic analyzers (ESA) onboard of a constellation of small satellites. Figure 1 shows the geographical distribution of ground GPS-TEC stations chosen for this study. In the OSSE, the simulated weather (true) time-dependent ion and electron density distributions are generated by using again the IPM model. For this study we have used two geomagnetically quiet days, 2010 day 73 and 74 (March $14^{th}/15^{th}$) where Kp~1 throughout the two days. These two days were chosen to assist in another study comparing actual MESA data from the MISSE7 experiment on the ISS with the GAIM predictions; that work is outside the scope of this paper. For the simulations we varied the equatorial vertical drift and horizontal neutral winds by superposing on the climatology values a random component. Note that neither the climatological values nor the random components are known to the ensemble Kalman filter part. The synthetic data were then generated by probing the 3-D, time-dependent electron density distribution for the weather (true) simulation exactly the same way the real instruments probe the real ionosphere. For the GPS receivers, slant TEC values were generated only for elevation angles greater than 15°. For the in-situ electron densities synthetic observations were generated in 10-sec increments. When the synthetic data were generated, noise

was added to each ‘‘measurement’’ in order to mimic a real observation. A 5 TEC unit (TECU) level of noise was added to all simulated TEC measurements and a 10% uncertainty to the simulated in-situ measurements. . It should be noted that the 10 second resolution of the observations is not intended to capture variations that occur on this small time step, but instead to capture spatial variations of the order of about 100-150 km around the latitudinal resolution of the model. 10 seconds is also the nominal cadence of data-taking in the IMESA instrument (although it is capable of running as fast as 2Hz). The satellites traverse a distance of about 70 km in 10 seconds, which provides about two observations per latitude grid cell. The model time step of 15 minutes was chosen to capture typical variations in the ionospheric F-region where the characteristic timescales are of the order of tens of minutes.

The ensemble Kalman filter assimilation procedure was implemented as follows. At 0000 UT on day 2010/073 the plasma distribution obtained from the “truth” run (the IPM run with the modified climatological neutral wind and equatorial electric field input) was taken to be the initial distribution at the start of the assimilation. Every 15 min, the evolving weather simulation was probed to obtain the two synthetic data types (with noise) as described above. At these time marks the ensemble of ionosphere/plasmasphere model runs was also integrated forward in time, and the model error covariance matrix was determined [Scherliess et al., 2007]. Using the new data and the new error matrix, the ensemble Kalman filter reconstructed an updated estimate of the plasma distribution and its drivers. The new drift and wind velocities were fed back into the IPM and the assimilation was repeated at the next 15 min time mark. As time advanced, the ensemble Kalman filter produced a 3-D, time-dependent, plasma distribution that got closer and

closer to the 'true' plasma distribution associated with our weather simulation

To qualitatively and quantitatively assess the impact of the MESA observations on the plasma specifications four ensemble Kalman filter simulations were performed. Initially, the GAIM-FP model assimilated only the simulated global TEC data to obtain a specification of the plasma density for the two days. This model simulation is referred to as the "ionospheric specification" and may be compared with the "truth" measurement to determine the accuracy of the data assimilation model.

Next, the synthetic MESA "observation", including an observational uncertainty, were assimilated together with the synthetic global TEC data to simulate data-taking from satellite constellations that did not, in reality, exist at that particular time. The simulated observations were taken along satellite tracks for three different orbital scenarios at 10 second simulated cadenceThe orbital scenarios were chosen to give both low-cost (single launch) rapid re-coverage of a localized area, and higher-cost (multiple launches) global coverage. We also wished to investigate effect of varying the altitude of the satellites on the sensitivity of the specification. Accordingly, the three orbital scenarios chosen were as follows:

Scenario A: Ten satellites in a circular 500 km polar orbit (90° inclination) at longitude 161.25° E (the Pacific sector, where GPS TEC ground stations are relatively sparse compared to over continental land masses). Small (deliberate) variations in the satellite surface treatment will lead to small variations in satellite drag, causing the satellites to distribute themselves along the orbital path until they are spread evenly along the orbit. This represents the "string of pearls" configuration for a single launch/deployment.

Scenario B: As scenario A, but at a 350 km altitude.

Scenario C: A 25/5/1 Walker constellation at 510 km altitude and 60° inclination. The Walker constellation notation of *t/p/f* designates *t* satellites arranged over *p* evenly spaced orbital planes (circular orbits) with *f* relative spacing between satellites in adjacent planes. Thus, a 25/5/1 constellation has 25 satellites, five satellites per orbital plane. We have picked a nominal relative spacing in this instance. This would generally require five launch vehicles, each deploying five satellites, with each group deploying into the string of pearls configuration after some weeks. Figure 2 shows (lower panel) Ne at 510 km, and (upper panel) the ground tracks of a 25/5/1 Walker constellation with the color scale along each ground track demonstrating the sampling of Ne.

For each of the three orbital scenarios the GAIM-FP model was used together with the global TEC inputs and the MESA "observation" to obtain another set of specifications of the same day. These model simulations are referred to as the "improved ionospheric specification", and may be compared to the original "ionospheric specification" (without any MESA data inputs) and the original "truth" model run.

5. Results

For Scenarios A and B, we have examined a vertical slice of the ionosphere from 100 km to 600 km along the 161. 25° E line of longitude of the orbital plane, stretching from 60° N to 60° S. (Plots are plotted to the poles, but the GAIM model used only extends to +/-60° magnetic latitude). Figure 3 shows the deviation from "truth" in units of ΔNe (cm^{-3}) for three simulation runs: "ionospheric specification" using only GPS-TEC inputs to the assimilative forecast model

(left panel), "improved ionospheric specification" using GPS-TEC inputs plus inputs from satellites in scenario A (center panel) (satellites at 500 km), and "improved ionospheric specification" using GPS-TEC inputs plus inputs from satellites in scenario B (right panel) (satellites at 350 km).

A visual inspection of the data shows that utilizing inputs from a modest constellation of ten satellites at either of two altitudes shows a distinct improvement to the "improved ionospheric specification" (ΔNe converges towards zero). What is perhaps remarkable is that the improvement is distinct at most latitudes and can be seen at all altitudes and not just at the orbital altitude. The apparent propagation of information to other altitude regimes is a manifestation of the strong correlation of electron density variations along geomagnetic field lines. These correlations are part of the ensemble Kalman filter and automatically calculated using the ensemble of physics-based model runs.This indicates that the useful life of such a constellation, as orbital drag decays the orbit from the initial insertion, will be extended through the life of the mission (months to years for higher initial orbital insertions), rather than losing their use after initial orbital decay.

Scenario C allows inspection of global (latitude-longitude) coverage. We have elected to use hmF2 as a proxy for our knowledge of the ionosphere (remembering that although the satellites in Scenario C are at 500 km, the earlier results indicate that information is apparently propagating vertically (owing to the correlation of electron density along magnetic field lines in the ensemble Kalman filter) allowing us to inspect the ionosphere and the improvement to the plasma specifications at any altitude). We inspect hmF2 at an arbitrary time of 1600 GMT on day 2. Figure 4 shows hmF2 from the "truth" model (plotted to the latitude limits of the model)

at the selected time. Figure 5 shows hmF2 obtained from the "ionospheric specification" model using only GPS-TEC inputs to the model. A visual inspection shows that there are deviations from "truth". In particular, the height enhancement over the Japanese sector is not found; there is an erroneous equatorial plume forecast over the Indonesian sector; and the pronounced equatorial anomaly over the South American sector is not seen in the data assimilation results for this limited model run.

Figure 6 shows hmF2 obtained from the "improved ionospheric specification", utilizing GPS-TEC inputs plus simulated data from the MESA instruments in the Walker constellation of scenario C. Inspection shows that the three features mentioned above, reproduced poorly by the "ionospheric specification", are present in the "improved ionospheric specification".

The previous examples are qualitative. There are many quantitative metrics that can be used to quantify the improvement, and we have arbitrarily selected two metrics, the RMS deviation (global sum) and the Skill Score (global sum). The RMS deviation, summed over all latitude-longitude points at each hmF2 altitude, is given by the sum of the squares of the deviations from truth divided by the number of observations and is measured in km (equation 1). Improved modeling will reduce the RMS deviation towards zero.

The Skill Score is a measure of improvement of one model over another and is unitless, ranging from –infinity to +1. If the second model is perfect the Skill Score tends to +1, and if the second model predicts no better than random chance the Skill Score tends towards 0 (equation 2).

$$RMS = \sqrt{\frac{\sum(Truth - Obs)^2}{N}} \qquad (1)$$

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$$Skill\ Score = 1 - \frac{\sum\left(Truth - (GPS+IMESA)\right)^2}{\sum(Truth - GPS\ only)^2} \quad (2)$$

Figure 7 shows the RMS deviation from truth global sum over a 24-hour period on 2010 day 073. With the "ionospheric specification" (GPS-TEC only), the RMS deviation from truth varies between 25 km and 100 km over the course of the 24 hours. It is interesting to note the variation over time, and we suggest that this is due a function of daytime and nighttime regions being densely or less densely populated with GPS-TEC ground stations, as the sun moves from the Pacific sector (less densely populated with GPS-TEC ground stations) to the American and European sectors (more densely populated). With the "improved ionospheric specification" (GPS-TEC plus simulated MESA data from scenario C), which of course are agnostic to day-night variations, the RMS deviation global sum improves to around 10 km over the course of the day.

The Skill Score comparison of the two model runs is shown in Figure 8. Again we see a pronounced diurnal response, with the "improved ionospheric specification" performing extremely well in the 0000 UT to 0600 UT, and 1800 UT to 2359 UT timeframes, and marginally less well between those timeframes. However, with the Skill Score minimum being ~0.75, we can conclude that overall there is a marked improvement to our forecast model with 25 MESAs in orbital scenario C.

We recognize that the results obtained from these metrics can depend on other parameters such as geomagnetic activity, but such an investigation is outside the bounds of this paper.

6. Conclusions

We have proposed using a simple sensor that measures ion and electron energy spectra, from which plasma density and temperature can be derived, in a low-cost mission of small satellites/sensors. A full physics ionospheric model has been utilized to derive "truth" data. The GAIM-FP forecast model has then been run both without and with simulated sensor data inputs. Our model simulations have shown that adding a constellation of small satellites/sensors in addition to global TEC inputs converges the GAIM-FP model closer to "truth" in the situations we describe. For a real-life mission for which a launch has not been imposed, a desired improvement metric may be selected and thus orbital parameters can be fine-tuned to optimize the model improvement for the metric of interest.. What is particularly interesting is that the model is improved over a range of altitudes, not just at and around the satellite/sensor altitude, emphasizing the coupled nature of both the model and reality, (and in particular here, the strong correlation of electron density along geomagnetic field lines in both the model and reality). Put another way, knowledge at one location leads to improved knowledge at other locations.

However, what has become apparent is the challenge to develop a generally agreed metric or set of metrics to measure the scientific and operational benefit to assimilative models from the use of multiple small satellite/sensor inputs.

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Figures

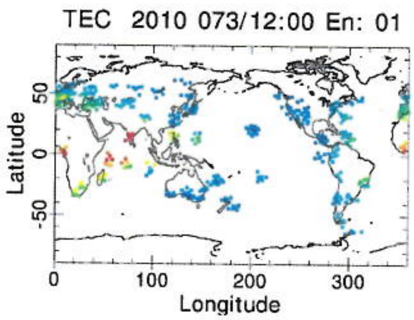

Figure 1: Geographical distribution of ground-based GPS-TEC stations chosen for this study. The figure shows the 300 km pierce points of observations at the given time (2010/073 1200 UT), and the color scale depicts vertical TEC with blue indicating low TEC and red indicating high TEC.

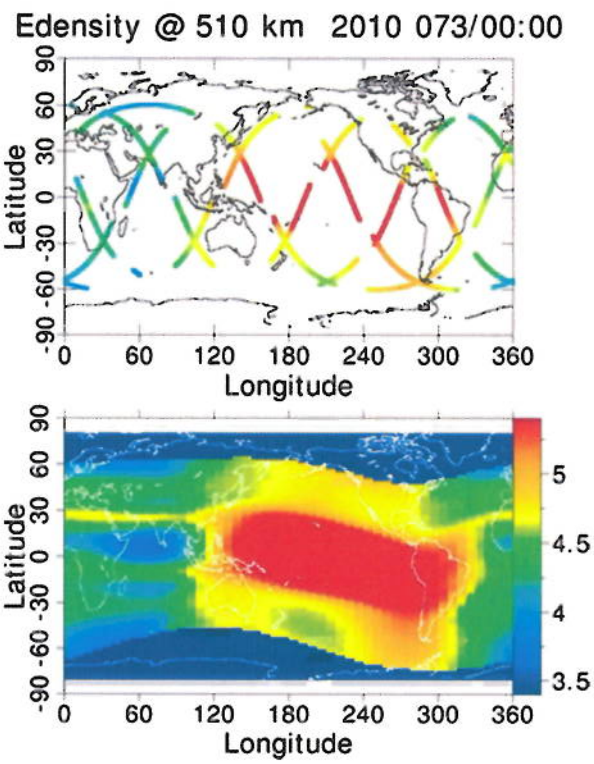

Figure 2: (upper panel) 25/5/1 Walker constellation ground tracks showing sampling of Ne from "truth" model run , and (lower panel) snapshot of Ne obtained from an "improved ionospheric specification" forecast model (GPS-TEC and sampled MESA data)

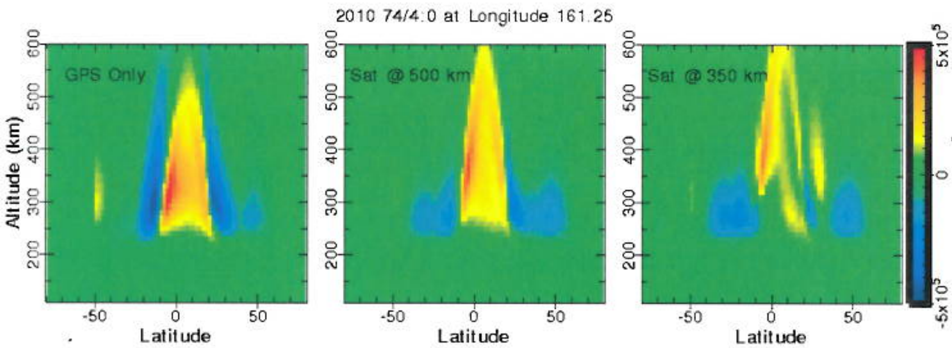

Figure 3: Model deviations from "truth" run for scenarios A and B, over the altitude-latitude slice at longitude 161.25°E. Changes in Ne are denoted by variations in the color scale from green (no deviation).

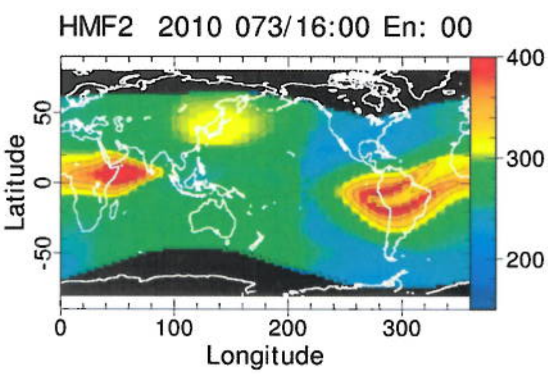

Figure 4: "Truth" model of hmF2

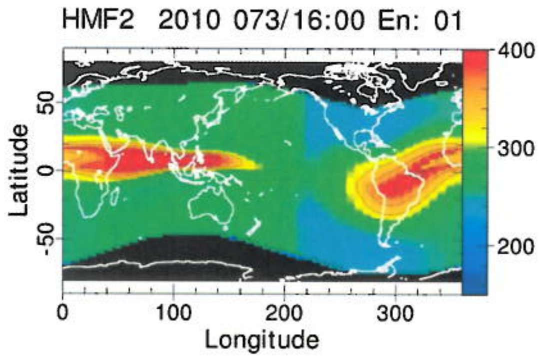

Figure 5: hmF2 "ionospheric specification" model of hmF2 using only GPS-TEC inputs to the GAIM-FP model

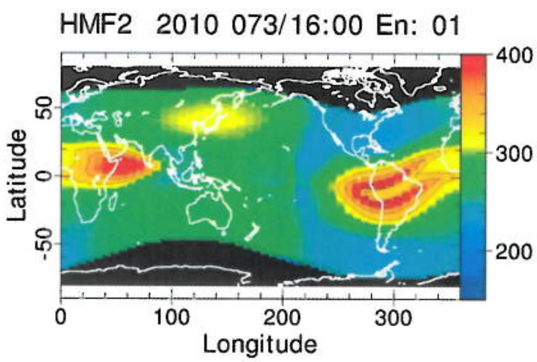

Figure 6: hmF2 "improved ionospheric specification" model of hmF2 using GPS-TEC and in-situ MESA data

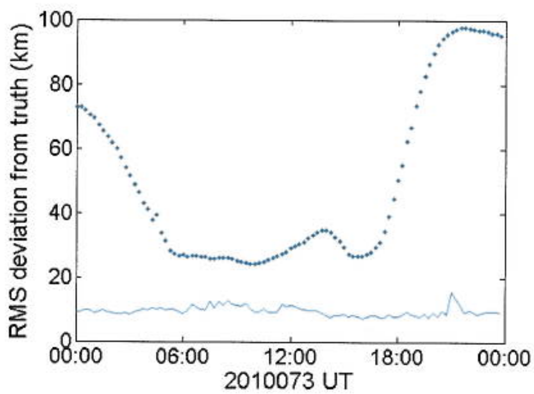

Figure 7: RMS deviation of hmF2 prediction (global sum). The upper (dotted) line shows predictions from the "ionospheric specification" (GPS-TEC only); the lower (solid) plot shows the predictions for "improved ionospheric specification" (GPS-TEC and MESA inputs).

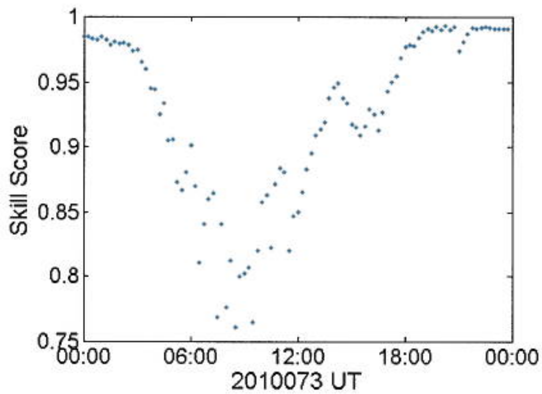

Figure 8: Skill Score of hmF2 prediction, comparing "improved ionospheric specification" to "ionospheric specification".